Properties of Cometary Nuclei

J, Rahe,
NASA Headquarters, Washington, DC

V. Vanysek,
Charles University, Prague, Czech Republic

P. R. Weissman
Jet Propulsion Laboratory, Pasadena, CA

Abstract: Active long- and short-period comets contribute about 20 to 30% of the major impactors on the Earth. Cometary nuclei are irregular bodies, typically a few to ten kilometers in diameter, with masses in the range 10^{*5} to $10^{'8}$ g. The nuclei are composed of an intimate mixture of volatile ices, mostly water ice, and hydrocarbon and silicate grains. The composition is the closest to solar composition of any known bodies in the solar system. The nuclei appear to be weakly bonded agglomerations of smaller icy planetesimals, and material strengths estimated from observed tidal disruption events are fairly low, typically $1\&$ to 10^4 N m^{-2}. Density estimates range between 0.2 and 1.2 g cm^{-3} but are very poorly determined, if at all. As comets age they develop nonvolatile crusts on their surfaces which eventually render them inactive, similar in appearance to carbonaceous asteroids. However, dormant comets may continue to show sporadic activity and outbursts for some time before they become truly extinct. The source of the long-period comets is the Oort cloud, a vast spherical cloud of perhaps 10^{12} to $10^{'3}$ comets surrounding the solar system and extending to interstellar distances. The likely source of the short-period comets is the Kuiper belt, a ring of perhaps 10^8 to 10^{10} remnant icy planetesimals beyond the orbit of Neptune, though some short-period comets may also be long-pcriod comets from the Oort cloud which have been perturbed to short-period orbits.

Int reduction

Comets account for ~ 20 to 30% of the major impacts on the Earth, those where the crater diameter is > 10 km and/or the impactor diameter is > 1 km (Shoemaker et al. 1990; Weissman 1990a), Virtually the entire mass of a comet is concentrated in its solid, relatively small nucleus which has a typical diameter of several to ten kilometers. If such a body, with an estimated average mass of 10^{15} to 10^{18} grams would strike the Earth with a velocity ranging between 16 and 72 km s^{-1}, the energy released in the impact would be in the range 10^{27} to 10^{31} ergs, equivalent to 1@ to 109 megatons of explosives, The consequences of such a catastrophic impact on the Earth's global environment could be extremely serious and have long-lasting effects.

Our direct knowledge of cometary nuclei is relatively poor. When active, they are unresolvable using Earth-based telescopes, buried deep within the bright cometary comae. When inactive (and it is uncertain if cometary nuclei are ever really inactive while they are within the planetary system), they are often too distant and faint for many diagnostic techniques used in asteroid studies to be applied to them. The only spacecraft missions to comets so far have been the ultra-fast flybys of comet Halley in 1986, and the follow-on Giotto flyby of comet Grigg-Skjellerup in 1992. Although these missions provided a wealth of new information, they left many questions about the nature of cometary nuclei and cometary processes unanswered. Those unanswered questions require future cometary exploration missions which will rendezvous with a cometary nucleus and follow it through its orbit, watching the onset and decline of cometary activity, and studying the nucleus in detail at close range.

In the following, we review the current state of knowledge of cometary nuclei and relevant parameters for the hazards problem, both in defining the estimated hazards and in

formulating impact mitigation technologies, We also provide a brief description of cometary dynamics and suggestions for further reading on that topic. Detailed estimates of cometary impact rates are left to the chapters on that subject for long-period comets (Marsden and Steel) and short-period comets (Shoemaker et al.). Some consequences of impacts peculiar to comets will be briefly discussed.

Dimensions and Albedos of Cometary Nuclei

The only resolved images of a cometary nucleus are those obtained in 1986 of the comet Halley nucleus by the Giotto spacecraft multicolor camera (Figure 1; Keller 1987) and those, with somewhat lower resolution, obtained by the Vega 1 and 2 spacecraft cameras (Figure 2; Sagdeev et al. 1986a). The nucleus appears as a highly irregular ellipsoid with dimensions of ~ 15 x 8 x 7 km. It is one of the darkest bodies in the solar system with a measured surface albedo of 0.035 to 0.045 . Active areas on the Halley nucleus were confined to discrete areas comprising about 10% of the surface area visible in Figure 1, or perhaps 20 to 30% of the total nucleus surface area, Irregular surface topography with typical scale lengths of hundreds of meters was visible, but difficult to interpret because of the modest resolution of the Giotto and Vega images. The nucleus occupies a volume of ~ 365 km^3 (Szegö 1991). Because of the high velocity of the flybys, the mass of the Halley nucleus could not be measured; it has been estimated indirectly (see below).

Past estimates of cometary albedos were fairly high (e.g., Delsemme and Rud 1973), which led to relatively small estimates for the dimensions of cometary nuclei, based on observations of what were assumed to be bare cometary nuclei (i.e, nuclei without surrounding comae) at large heliocentric distances, This in turn led to fairly low estimates for nucleus

masses, making them relatively unimportant among potential terrestrial impactors. However, the spacecraft measurements of comet Halley's nucleus, as well as more recent photoelectric and radiometric measurements of other nuclei indicate that the albedo of most cometary nuclei appears to range from 0.02 to 0.1, with a typical value of about 0.04, Thus, the nuclei are much larger than previously thought, and mass estimates have increased accordingly.

A listing of radii, albedo, and other relevant parameters for cometary nuclei is given in Table 1. The columns in Table 1 are: the mean radius in km, the ratio between the major and minor axes of the nucleus (derived from rotation light curves), the visual albedo, comments on the nucleus color, the rotation period in hours, and the measured gas production rate and the distance from the Sun at which it was measured. All of the listed comets have short-period orbits, with the exception of comet IRAS-Araki-Alcock. The dimensions of the nuclei can usually only be determined with an accuracy of about ±0.5 km. The elongated, prolate shape of Halley is seen to be typical for other comets as well,

The size distribution of cometary nuclei is not well known (see next section) and much smaller cometary nuclei as well as much larger ones may exist; e.g. the Great Comet of 1729 that could be seen with the naked eye at 4 AU from the Earth and Sun. The largest known cometary nucleus may be 2060 Chiron, an outer solar system "asteroid" (a = 13.7 AU, q = 8.5 AU) with geometrical albedo >0.027 and corresponding radius < 186 km (Sykes and Walker 1991). Despite its original classification as an asteroid, Chiron has been observed to display sporadic outbursts and a cometary coma (Meech and Belton 1989, 1990), even near its aphelion of 18.9 AU (Bus et al. 1991).

Densities" and Masses

The ratio of mass to volume yields the average density of cometary nuclei. In practice, the density is very difficult to determine because both mass and volume are so uncertain, Attempts to date to measure the mass of cometary nuclei have generally been based on comparing the nucleus activity with estimates of the nongravitational forces estimated from the comet's motion. For comet Halley, estimates of the bulk density based on modeling of nongravitational forces range from 0.2 to 1.2 g cm^{-3} (Rickman 1986, 1989; Sagdeev et al, 1988; Peale 1989), with error bars covering an even larger range of values. The uncertainties involved in estimating nongravitational forces appear to make this method too unreliable.

An alternative method for estimating density is to consider the low-temperature, low velocity accretion of ice and dust grains in the solar nebula, yielding values ~0.3 to 0.5 g cm^{-3} (Greenberg and Hage, 1990). However, such estimates ignore subsequent thermal and physical processing of cometary materials which will tend to compact the ice-dust mix. On the other hand, densities determined for somewhat larger though still modest sized bodies in the outer solar system, Pluto, Charon, and Triton, are all -2 g cm^{-3} (Beletic et al, 1989; Tyler et al. 1989). The relatively high dust-to gas estimates derived from IRAS observations of cometary dust trails by Sykes and Walker (1992) tend to support the possibility that these higher densities may also be present in comets. Also, measurements of the density of collected interplanetary dust particles (IDP's), believed to be derived from cometary nuclei, yield values of ~0.7 to 1.2 g cm^{-3} (Fraundorf et al. 1982), despite the fact that the volatile ices have been lost from the particles.

Mass distributions for comets have been estimated indirectly from the distribution of the intrinsic (or "absolute") magnitudes, H_{lo}, of the observed comets. One suggested distribution

by Weissman (1990a) is shown in **Figure 3.** This distribution is based on the distribution of absolute magnitudes (with coma) after correction for observational selection effects, as found by Everhart (1967). This is necessarily y a tenuous estimate in that it seeks to relate the nucleus' size to its gas producing ability, a relationship that is likely neither simple nor obvious. For comets brighter than $H_{10} = 11$, Weissman (1990a) found the mass-magnitude relationship

$$\log m = 20.0 - 0.4 \log H_{10} \qquad (1)$$

where m is the nucleus mass in grams and a density of 0.6 g cm^{-3} is assumed. The magnitude $H_{10} = 11$ corresponds to a radius of 1.2 km and a mass of 4×10^{15} g. Using the magnitude distribution in Figure 3, the average cometary nucleus (brighter than $H_{10} = 11$) has a mass of 3.8×10^{16} g. Bailey and Stagg (1988) derived a similar mass-magnitude relationship

$$\log m = 19.9 - 0.5 \log H_{10} \qquad (2)$$

though with a steeper slope such that mass decreases more sharply with increasing absolute magnitude. Fernandez and Ip (1991) combined equation 2 with Everhart's brightness distribution to give for the mass distribution relationship, $N(m) \propto m^{-0.58}$ for masses $< 10^{17}$ g and $N(m) \propto m^{-1.16}$ for $m > 10^{17}$ g. Alternatively, assuming that the size data published by Shoemaker et al. (1990) for asteroids in the mass range 10^{15} to 10^{18} g crossing the Earth's orbit are also representative for cometary nuclei, then the distributions of cometary radii, r, and mass are given approximately by $N(r) \propto r^{2.5}$ and $N(m) \propto m^{-0.83}$.

Nucleus Structure

The surface morphology and the internal structure of cometary nuclei are unknown. A variety of models have been suggested (Whipple 1950, 1951; Dorm et al. 1985; Weissman 1986; Gombosi and Houpis 1986; see also reviews by Dorm 1991 and Rickman 1991). Several of

these models are illustrated in Figure 4. The current consensus is that the typical nucleus can be described as a porous and fragile body composed of fine grained refractory material, intimately mixed with hydrocarbon grains and volatile ices. It is believed that cometary nuclei are weakly bonded, fractal assemblages of smaller icy-conglomerate planetesimals of diameter ~ 1 km, possibly "welded" into a single body by thermal processing and sintering. Dynamical scattering of planetesimals by the outer planets may have resulted in mixing and assemblage of planetesimals formed in different temperature regimes; observational evidence for such heterogeneity has been found for comet Halley (Mumma et al. 1993a). In some cases (e.g., Fink 1992; Schleicher et al. 1993) observed compositional differences in comets are so great as to suggest formation in distinctly different regions of the solar nebula (i.e., the Jupiter-Saturn zone rather the than Uranus-Neptune zone).

Based on the images of comet Halley as well as observations of other comets, a tri-axial, irregular ellipsoid may be an acceptable model for a cometary nucleus. Several attempts have been made to explain the nonsphericity (Daniels and Hughes 1981; Jewitt and Meech 1988; see also Dorm 199 1), which seems to be a common property of cometary nuclei. These studies were based mainly on random-walk schemes for the aggregation processes. Although some results indeed lead to irregularities and deviation from sphericity, a tendency toward tri-axial shapes was obtained only by the numerical experiments by Jewitt and Meech (1988).

Mass-loss may also change the shape of cometary nuclei. At the time of the Giotto flyby, comet Halley was losing gas and dust at a rate of $\sim 3 \times 10^7$ to 10^8 g s^{-1} (see Hughes 1991). The total estimated water loss per orbital revolution is $\sim 3 \times 10^{14}$ g (Feldman et al. 1987). Adding in other volatiles and assuming a dust-to-gas ratio of 2 raises the total mass loss to $\sim 1.1 \times 10^{15}$ g, equivalent to the loss of a surface layer of average thickness ~ 3.0 meters

with density 1.0 g cm^{-3}.   Because activity appears to come from discrete areas on the nucleus surface, an average erosion rate of $\sim$ 10 to 15 meters per revolution could be expected from those active areas. Therefore, one might expect that the mass loss could lead to some irregular evolution of surface features, though possibly not to gross changes in the shape of the overall nucleus.

Rotation of Cometary Nuclei

Although there are about 60 reported determinations of rotational periods of cometary nuclei (e.g., Sekanina 1981; Whipple 1982), only a few appear to be reliable, and even they do not necessarily describe the true rotational state.   The determination of spin state, i.e rotation period and orientation of the spin axis, is based on the search for periodicities in time-series of some continuously varying observed property of the comet, mainly a variation in its brightness,

The difficulties one encounters when attempting to determine the spin parameters of cometary nuclei can be demonstrated with the case of comet Halley. Although early published results indicated that the nucleus rotated with a period of 2.2 days around the shortest axis (Sekanina and Larson 1984; Kaneda et al. 1986; Sagdeev et al. 1986b), i.e. in the "ground" state, strong evidence later emerged for a period of 7.4 days (Minis and Schleicher 1986, Stewart 1987). More detailed examination of the data suggested that the nucleus of comet Halley rotates as an asymmetric top (Belton et al, 1992), in which it is assumed that the nucleus rotates around both the long and short axes. In the most likely mode, the long axis executes a precessional motion around the space-fixed total rotational angular momentum vector with a period near 3.7 days, while performing a "nodding" with a period of about 7.3 days (Samarasinha and A'Hearn 1991).

The available data on rotation for seven periodic comets, including comet Halley, indicate that the cometary nuclei rotate in an excited energy state (Belton 1991). The characteristic time, t, for an oblate rotator (and to first approximation, for other shapes) with frequency ω to relax to a state of principal axis rotation (i .e., the time necessary for damping of the wobble motion) is given by (Bums and Safronov 1973)

$$t = \mu\, q\, Q\, \omega^3 / \rho\, R^2 \qquad\qquad (3)$$

where μ is the rigidity or shear modulus of the cometary nucleus, *p is* the density, Q is a dimensionless measure of internal energy dissipation per rotation cycle, R is the "mean" radius and q $= 38/5$ for a nearly homogeneous body, Peale and Lissauer (1989) suggest $t = 10^6\, Q$ years for cometary nuclei, assuming the shear modulus for ice, with $Q \leq 10^2$ and even $Q \leq$ 1, while Burns and Safronov suggest typical values for Q for asteroids of 1(? to 10^3. The rigidity of the cometary material is most likely much lower than that for asteroids and the shear modulus could be $\sim 10^7\, N\, m^{-2}$, which is about 0.01 times that of solid water ice. Even with Q $= 1$ the relaxation time in the rotational characteristics of cometary nuclei could be $t \simeq 1\, 0^6$ years, comparable to typical dynamical lifetimes of short-period comets, and likely much longer than their physical lifetime as active objects.   The excitation into higher rotational states for cometary nuclei is most probably a result of nongravitational forces from jetting on the nucleus surface. Since the damping time scale is long compared to the orbital period, the excitation of the rotational state is probably a cumulative process.

Another question is the orientation of the spin vector. The original spin characteristics may be modified and/or randomized by nongravitational forces and mass loss. As already noted, cometary nuclei lose substantial mass during their active phases. This process is not expected to lead to dramatic changes in the spin (Peale and Lissauer 1989), but may be responsible for

a secular; systematic drain of the angular momentum resulting in "spin-down" of the nucleus. This may account for the apparently lower mean rotation frequencies for cometary nuclei as compared with comparably sized asteroids.

Material Strengths

Little is known about the strengths of cometary materials. Observational evidence, i .e., splitting of comets, as well as theoretical considerations suggest that the cometary nuclei are poorly consolidated bodies. Statistics show that about 10% of "dynamically new" comets (those coming in from the Oort cloud for the first time) randomly disrupt during their first passage through perihelion. Similar random disruption events are observed for ~ 4% of long-period comets making subsequent returns, and -1 % of short-period comets (Weissman 1980; see also Sekanina 1982). The disruption events show no obvious correlation with time relative to perihelion, perihelion distance, orbital inclination, or the ecliptic plane. Presumably, the events are associated with thermal stresses generated by the heating the nuclei receive as they approach and recede from the Sun. The disruption events could be regarded as a selection process, whereby comets which are likely to split do so rather rapidly, while others are more stable and survive many perihelion passages (Weissman 1980; Sekanina 1982). Comet Halley appears to belong to the latter group.

A second class of observed disruption events are those caused by passage through the Roche limit of the Sun or a planet. This has been seen for many members of the Kreutz group of Sun-grazing comets (Marsden 1967, 1989) and for two short-period comets which passed close to Jupiter: P/Brooks 2 (in 1886) and comet Shoemaker-Levy 9 (in 1992; see Shoemaker et al. 1993). Although all members of the Kreutz group pass within a solar radius of the Sun's

photosphere, and some have been observed to impact the Sun, not all of them are observed to disrupt during their perihelion passage,   In the cases of the short-period comets, both were discovered as double (Brooks 2) or multiple (Shoemaker-Levy 9) nuclei, after their close passages to Jupiter.

There are two different concepts for analytical studies of tidal breakup: "tidal disruption" and "tidal failure. "   Boss et al. (1991) defines "tidal disruption" as a process whereby a body is tidally separated into two or more pieces which subsequently move on individual orbits. This concept can be applied to the case of inviscid bodies which are held together by gravity and not by internal forces.   The "tidal failure" concept is based on a comparison of tidal stresses to material strengths of solid bodies (Aggarwal and Oberbeck 1974; Dobrovolskis 1990; Sridhar and Tremaine 1992). The latter concept is the better for obtaining an understanding of material strengths in cometary nuclei. A similar comparison can be made between centrifugal forces and material strengths if the size and rotation of the nucleus is known.

Sekanina and Yeomans (1985) determined tensile strengths of $\sim 10^2 \, N \, m^{-2}$ from an anal ysis of the tidally disrupted Sun-grazing comets 1882 II and 1965 VIII. For survival of a Sun-grazing cometary nucleus with radius = 5 km, density = 0,5 g cm^{-3}, and perihelion q = 0.005 AU, the minimal required value of tensile strength is about $3 \times 10^3 \, N \, m^{-2}$. Whipple (1982) derived an upper limit on tensile strength of about $10^4 \, N \, m^{-2}$ from cometary spin and sizes statistics. These values are all very low as compared with values for common materials. For example, the "breaking strain" for rocky materials is $\sim 4 \times 1@ \, N \, m^{-2}$, and $\sim 2 \times 106 \, N \, m^{-2}$ for solid water ice.

Surface Processes

The source of cometary activity is the sublimation of volatile ices on the nucleus surface (Whipple 1950, 1951). The evolving gases, mostly water, carry with them micron sized grains of dust and hydrocarbons, forming the comet's extended atmosphere, or coma. Ions formed in' the coma are carried back by the solar wind to form the bright Type I plasma tails, while dust grains are blown back by solar radiation forces to form the broader, more curving Type II tails.

The surface temperature of an icy-conglomerate mix exposed to sunlight is found by balancing the incoming solar radiation with outgoing thermal radiation, heat conducted into the cometary interior, and energy used in sublimation (Weissman and Kieffer 1981)

$$SO \ r^{-2}(1 - A) \cos i = \epsilon \sigma T^4 - K \ \delta T/\delta z \mid_{z=0} - L \ \delta m/\delta t \qquad (4)$$

where SO is the solar constant, r is the heliocentric distance of the comet, A is the surface bond albedo, i is the local solar zenith angle, ϵ is the emissivity, σ is the Stefan-Boltzmann constant, T is the temperature, K is the conductivity, $\delta T/\delta z$ is the temperature gradient evaluated at the surface, L is the heat of sublimation, and $\delta m/\delta t$ is the mass loss (sublimation) rate. At large solar distances both the conduction and sublimation terms are small and the surface temperature acts similarly to an inactive asteroid. At about 5.8 AU, water ice located at the sub-solar point on the nucleus can begin to sublimate but the total production rate remains low because of the very small surface area involved. At about 3 AU water ice sublimation begins to become significant for the entire nucleus, at surface temperatures ~ 160 - 175 K. By 1.5 AU sublimation typically dominates the energy outflow, buffering the nucleus surface temperatures at -200 to 220 K. Other more volatile ices, such as CO and HCN, can begin to diffuse out of the ice-dust mix at large solar distances, and will continue to be liberated as the overlying ice-dust layers are sublimated away, and the solar heating wave penetrates to greater depths within

12

the nucleus.

Few comets actually match this highly idealized physical picture, though their gross behavior usually follows it somewhat. The situation is complicated, in part, by the existence of lag deposits of large non-volatile grains which develop on the nucleus surfaces, insulating the ices beneath them (Brin and Mendis 1979; Fanale and Salvail 1984). Estimates of the thickness of these lag deposits, or crusts, range from a few centimeters to meters. If the crusts become sufficient y thick and insulating, they can essentially "turn-off" the cometary ices beneath them. Alternatively, build-up of gas pressure from sublimating ices beneath the crusts may cause them to rupture, resulting in sudden visible outbursts. Sublimation may also lead to development of unusual surface morphologies, as have been seen on terrestrial glaciers and icefields.

It had been predicted that the surface of the nucleus of comet Halley would be free of crust because of the high activity that comet reaches at its perihelion of only 0.587 AU. Thus, it was somewhat of a surprise to discover that ~ 70 to 80% of the nucleus was covered by an apparently inert crust. Subsequent studies of other short-period comets (A'Hearn 1988, Weissman et al. 1989) showed that the fraction of active surface area appears to decline with cometary age, reaching less than 1 % for some of the older short-period comets such as P/Arend-Rigaux and P/Neujmin 1. This leads to the interesting possibility that comets might evolve to completely inactive, dormant objects that would be asteroidal in appearance (see below).

Although comets are the most pristine bodies in the solar system and have essentially been in "cold storage" in the Oort cloud and Kuiper belt over most of their lifetimes, there are a number of physical processes which may have modified them in various ways. These include: irradiation by galactic cosmic rays and solar wind protons (Johnson et al. 1987), heating by supernovae and passing stars (Stem and Shun 1988), competing erosion and accretion by

interstellar dust grains (Stern 1986, 1990), and conversion from amorphous to crystalline ice (Smoluchowski 1981; Prialnik and Bar-Nun 1988). These, and several other possible modifying processes are depicted in Figure 5. All of these processes are fairly modest when compared with typical planetary processes such as giant impacts or differentiation and core formation. The low degree of processing is evidenced by the high volatile content of comets.

The radiation processing is particularly interesting because it too leads to development of a non-volatile surface crust, perhaps a meter in thickness, before the comet ever enters the planetary region. Thus, dynamically new comets may approach the solar system with inert crusts that must be removed, at least in part, for the comets to show any activity at all. That removal may be aided by the amorphous-to-crystalline ice conversion which is exothermic, and occurs for the first time as the comet approaches 5 AU from the Sun. New comets from the Oort cloud are anomalously bright at large solar distances, ~ 5 AU, on their first perihelion passage and this process may explain that distant activity.

Useful reviews on nucleus thermal and physical processing are provided by Rickman (1991) and Weissman (1990b).

Dormancy of Cometary Nuclei

In some well documented cases, periodic comets with well-determined orbits could not be recovered although they were in a relative] y favorable position for Earth-based observers. This suggests that some cometary nuclei could be inactive for long periods of time, making their recovery difficult, There appear to be considerable differences among comets in the length of dormant or low activity phases. For example, the interim dormancy of P/Arend-Rigaux (Minis et al. 1988) extended for three consecutive orbital periods, Much longer and extensive periods

14

of inactivity are implied for some comets, namely for P/Encke (Kresak 1987, Sekanina 1988) P/DeViCo-Swift, and P/Tuttle-Giacobini-Kresak (rediscovered twice). P/Tempel 1, P/Denning-Fujikawa and P/Peters-Hartley were each rediscovered after more than ten missed returns. Comets which demonstrate this behavior seem to be characterized by relative] y small nuclei and small perihelion distances.   The erosion rates of the active regions may be so great that the average activity time-scale of the individual sources on the nucleus is much shorter than the orbital evolution. Periods of dormancy interspersed with short periods of reactivation seem to be less typical for the larger cometary nuclei.   Cometary deactivation does not appear to be a monotonic process which terminates with an irreversible extinction of gas and dust production. More typical for the aging symptoms of comets seems to be somewhat erratic behavior characterized by intermittent periods of dormancy and reactivation.

Extinct Comets Among the Near-Earth Asteroids

The origin of the near-Earth asteroids has been the subject of an ongoing debate among solar system scientists for several decades now. Because they are in planet-crossing orbits, these objects have dynamical lifetimes of only $\sim 3 \times 10^7$ years (Wetherill 1975). Thus, the population of Earth-crossing asteroids must be continuous y replenished. The origin arguments largely split along discipline lines. In general, observers believed that the near-Earth asteroids were derived from the main asteroid belt between Mars and Jupiter, because they appeared similar spectroscopically y to main belt objects.   On the other hand, dynamicists favored a cometary source because of the lack of known dynamical mechanisms to move sufficient numbers of asteroids from the main belt to near-Earth orbits. However, in the past decade two dynamical mechanisms for delivery of main belt asteroids have been recognized which could account for

at least half of the estimated population of near-Earth asteroids (Wetherill 1988), while observational evidence has continued to mount of anomalous Earth-crossing asteroids whose characteristics and behavior might be explained if the objects were indeed extinct cometary nuclei. The recognition that ~ 70% of the surface of comet Halley was covered by an apparently inert crust was important in lending credibility to the idea that comets could evolve into dormant, asteroidal-appearing objects.

Various tests of cometary versus asteroidal origin have been put forward, usually based on statistical differences between the size, shape, rotation periods, spectral properties, meteor stream associations, and orbital dynamics of their parent populations (see Weissman et al. 1989). However, none of these tests are definitive, and many near-Earth objects display contradictory combinations of physical attributes. The one agreed-upon test of a cometary origin is the ability to generate an appreciable cometary coma around the nucleus. A number of independent observations do exist of what may well be sporadic activity in some near-Earth asteroids.

The possible evolution of short-period comets to inert-appearing, near-Earth asteroids has been reviewed extensively by Öpik (1963), Wetherill (1971, 1991), Degewij and Tedesco (1982), Kresak (1985), Fernandez (1988), and Weissman et al. (1989). The reader is referred to those papers and references therein for a more complete discussion of the problem. The reviews by Degewij and Tedesco and by Weissman et al, are particularly recommended as they arrive at rather opposite conclusions as to the likelihood of extinct or dormant comets among the near-Earth asteroids, and thus provide good examples of the two sides in the debate.

A list of comet-like asteroids and a detailed discussion of the characteristics that make each object a member of the list is given in Weissman et al. (1989). Probable cometary candidates identified among the numbered asteroids include: 944 Hidalgo, 2060 Chiron, 2101

Adonis, 2201 Oljato, 2212 Hephaistos, 3200 Phaethon, and 3552 Don Quixote; while possible candidates include: 1566 Icarus, 1580 Betulia, 1620 Geographos, 1685 Toro, 1862 Apollo, 1866 Sisyphus, 1917 Cuyo, 1981 Midas, and 2062 Aten.

As noted earlier, Chiron is indeed cometary as demonstrated by its sporadic activity around its orbit. Another example of a comet that apparently evolved to an asteroidal object is asteroid 4015 (1979 VA) which was independent] y discovered and cataloged as comet Wilson-Harrington in 1949 when it briefly showed coma activity (Bowell and Marsden 1992). Future observational surveys are likely to discover additional transitional objects like 4015 Wilson-Harrington, and to provide additional evidence for objects of cometary origin among the near-Earth asteroids.

Chemical Composition

The present knowledge of the chemical composition of cometary nuclei is inferred from measurements of neutral and ionized gases in the coma and tail, and from dust grains. These data are obtained primarily through ground-based spectroscopy at ultraviolet, visible, infrared, and radio wavelengths, and by *in situ* measurements by the spacecraft that encountered comet Halley in 1986. Earth-orbiting instruments and rocket-borne payloads have also provided valuable data.

Prior to the mid-1980's, most gaseous species accessible to ground-based observers were photo-dissociation products of parent molecules that sublimated from the cometary nucleus. However improvements in infrared and radio instrumentation, as well as *in situ* measurements by flyby spacecraft at Halley, led to direct measurements of the parent molecules. The abundances of parent molecules in comet Halley and other comets were recently critically

reviewed by Mumma et al. (1993a). The observed molecules, radicals, and ions in comets are summarized in Tables 2 and 3.

The dominant molecule in the volatile component is H_2O, representing $\sim$ 70% to 90% of the total abundance of volatiles. Other species clearly present in comet Halley at more than 1 % relative to water are CO, CO_2, H_2CO, and CH_3OH. Volatile abundances vary from comet to comet: CO ranges from 1 % to 30% of the water abundance (A'Hearn and Festou 1990); CH_3OH ranges from 1 % to 7% (Mumma et al. 1993b).

In situ mass-spectroscopy of dust grains in comet Halley revealed the presence of two distinct compositional classes of particles: refractory silicates which had been expected, and hydrocarbon grains, termed "CHON" because they contained only the light elements C, H, O, and N. Larger grains with more complex compositions were apparently composed of assemblages of these two particle types. The compositional signature of the cometary grains close] y matches that of anhydrous olivine IDP's, providing support for the belief that these recovered grains are cometary. An example of a suspected cometary IDP is shown in Figure 6. The IDP is a botryoidal ("cluster-of-grapes") assemblage of submicron silicate and hydrocarbon grains, The inter-grain spaces were presumably formerly filled with cometary ices,

The cometary hydrocarbon grains apparently also act as a source of volatiles in the cometary coma. This was demonstrated by jet structures visible in the emission lines of CN in Halley (A' Hearn et al. 1986), and by an increase in the relative abundance of CO farther from the cometary nucleus (Eberhardt et al. 1987), indicating the existence of an extended source, i.e., volatile grains in the coma.

Estimates of the dust-to-gas ratio in comets have ranged from 0.5 to 2, with current best estimates for Halley now tending to point to the latter, higher value (McDonnell et al. 1991).

Analysis of IRAS dust trails, i.e., large cometary grains in the orbits of short-period comets, have suggested even higher dust-to-gas ratios for many known comets (Sykes and Walker 1992).

Atomic abundances of elements obtained from mass-spectroscopy of the dust in the coma of comet Halley are summarized in Table 4. These abundances are in excellent agreement with solar composition, demonstrating that comets are indeed the best obtainable source of original solar nebula material.

Abundances of the stable isotopes of elements heavier than C, including O and S in the gas phase and in solids in cometary comae appear to be in agreement with other measured isotopic ratios in the solar system; these are shown in Table 5 (Vanysek 1991). The deuterium/hydrogen ratio in cometary ices matches the range of D/H in Uranus, Neptune, and Titan, as well as meteorites and terrestrial ocean water. These are all bodies which may have received their volatiles in the form of condensed solids (i.e., ices, hydrates). In contrast, the D/H ratio in comets is about an order of magnitude more than in Jupiter and Saturn, which likely received the bulk of their volatiles in the form of nebula gases. One explanation of such an enrichment is ion-molecule reactions at low temperatures in a dense gas phase environment in the presolar nebula.

Carbon isotope ratios, $^{12}C/^{13}C$, found for gases in cometary comae are, on average, $\sim 100 \pm 15$ (Kleine et al. 1991), slightly above but bracketing the terrestrial value. Mass spectrometry of Halley dust grains showed variations in $^{12}C/^{13}C$ between 10 and 1,000, likely reflecting the non-equilibrium chemistry in the presolar nebula and in the dense cloud core out of which the solar system formed. However, the bulk of the isotopic evidence suggests that comets formed out of the same compositional reservoir as the rest of the planetary system.

Cometary Dynamics

Cometary orbits are classified as either long-or short-period, depending on whether their orbital periods are greater than or less than 200 years, respectively, The long-period orbits are randomly oriented on the celestial sphere, whereas the short-period comets are generally confined to direct orbits with inclinations less than $\sim 35°$. In recent years the short-period orbits have been additionally subdivided into two groups: the Jupiter-family comets with periods between 5 and 20 years, virtually all of which are in low inclination orbits, and the Halley-family comets with periods, $20 < P < 200$ years, which tend to include high inclination comets as well. Long-period orbital periods range up to $\sim 10^7$ years,

It is only in the last several decades that comets have been recognized to be true members of the solar system. Approximately one-third of all long-period comets observed passing through the planetary system are on weakly hyperbolic orbits. However, integration of the orbits backward in time to points outside the planetary region, and conversion from a heliocentric to a barycentric coordinate system, showed that those comets in fact had highly eccentric but still gravitationally bound orbits. Planetary perturbations, primarily by Jupiter, scatter the long-period comets in orbital energy, either ejecting them on hyperbolic orbits or capturing them to more tightly bound ellipses.

The successful explanation of the observed energy distribution of long-period comet orbits was provided by Oort (1950) who proposed that the planetary system was surrounded by a distant spherical cloud of comets extending roughly halfway to the nearest stars. Random passing stars and galactic tidal forces perturb the comet cloud and provide the flux of long-period comets into the planetary region. Current estimates for the population of the dynamically active outer Oort cloud are $\sim 10^{12}$ comets (Weissman 1991). There is also expected to be a

massive inner comet cloud with 5 to 10 times the population of the outer cloud, but in orbits that are not easily perturbed except by very close stellar passages or encounters with giant molecular clouds in the galaxy (Duncan et al. 1987). The source of the Oort cloud is presumed to be icy planetesimals ejected by the growing proto-planets in the outer solar system, in particular Uranus and Neptune.

An additional suggested cometary reservoir is the Kuiper belt, a disk of remnant icy planetesimals beyond Neptune, proposedbyKuiper(1951). Because of their long orbital periods and the expected decreasing density of material in the solar nebula accretion disk beyond Neptune, this material never accreted into a large planetary body. Duncan et al. (1988) showed that this material was the likely source of the short-period comets, in particular the low inclination Jupiter-family comets,   The more randomly inclined Halley-family comets may be long-period comets from the Oort cloud which have been random-walked in energy down to their low semimajor axes by planetary perturbations, or Kuiper belt comets which have been scattered to higher inclination orbits. The first two members of the Kuiper belt, 1992 QB_1 and 1993 FW, were discovered in the past year (Jewitt and Luu 1992; Luu and Jewitt 1993).

Returns of known short-period comets and the possibility of impacts on the Earth can be predicted with high accuracy, though not quite as well as for asteroids because of nongravitational forces on the comets resulting from jetting of volatiles from the nucleus surfaces. Twenty-five short-period comets have been discovered in Earth-crossing orbits, though some of them are currently lost (possibly disrupted) or no longer Earth-crossing (see chapter by Shoemaker et al.). Returns of long-period comets can, in general, not be predicted; they appear randomly in time.

The most recent Catalogue of Cometary Orbits (Marsden and Williams 1992) lists   353

cometary apparitions, of which 671 are long-period comets, The remaining 682 are appearances by 170 short-period comets, 103 of them on two or more returns. The most observed comet is comet Encke with 55 returns, and the longest observed comet is comet Halley, seen on every return since 240 B.C. Recent useful reviews on the Oort cloud and cometary dynamics are provided by Weissman (1991) and Femandez and Ip (1991), and on short-period comets by Weissman and Campins (1993). An excellent recent review on cometary origin is that by Mumma et al. (1993a).

Consequences of Cometary Impacts

To first order, the impact of a comet on the Earth will be similar to an asteroid impact, in that it will deposit a large quantity of kinetic energy at some location on the surface. However it is worth considering some subtle differences in the nature of the impacts as a result of the typically higher velocities and lower densies and material strengths of cometary impactors. Some minor differences resulting from the different composition of comets are also possible.

A comet approaching the Earth on an impact trajectory will be more likely to tidally disrupt as it crosses the Roche limit, because of both its lower density and lower material strengths than for rocky or iron asteroids. However, there is insufficient time for the fragments to disperse prior to impact, The geocentric distance, d_E, at which a comet of density equal to 1 g cm^{-3} (and zero strength) will begin to disrupt is given by

$$d_E = 2 \left(\rho_E / \rho_c \right)^{1/3} R_E = 3.53 \; R_E \qquad (4)$$

where ρ_E and ρ_c are the density of the Earth and the comet, respectively, and R_E is the radius of the Earth. A short-period comet traveling at a mean impact velocity of 29 km s^{-1} (Weissman

1982) will take 556 seconds, or 9.3 minutes to travel from that radius to the Earth's surface, assuming a normal impact. If the fragments were to separate at 1 m sec^{-1}, they would strike at most only 556 meters apart (if the velocity impulse was tangential), still likely well within the mutual craters they would each form, assuming impactors more than a few hundred meters in size. Impact times and separation distances will be smaller for the faster long-period comets, but would be greater for oblique impacts. However, only the near-grazing impactors would likely have sufficient time to allow substantial crater separation.

Because of their low material strengths and typically higher velocities, comets will tend to break up in the atmosphere at higher altitudes due to aerodynamics stresses, than for comparably sized asteroids. For example, Chyba et al. (1993) estimate that a cometary impactor with the 15 megaton energy of the 1908 Tunguska explosion would have deposited its energy at an altitude of ~ 23 km for a short-period comet, and -29 km for a (higher velocity) long-period comet, as compared with ~ 9 km for a typical stony asteroid. The minimum size cometary impactor which could survive intact to strike the surface of the Earth is likely a few hundred meters in diameter (P. Thomas, personal communication).

Passage of a hyper-velocity impactor through the Earth's atmosphere has been suggested as a possible source of atmospheric pollution as a result of the frictional heating of the air along the impactor's path (Lewis et al. 1982). Pollutants would include NO_2 and HNO_3 and might result in global smog and/or acid rain. Because of their higher velocities and propensity for fragmentation, comets will likely produce more such pollutants than comparably sized asteroids entering at lower velocities.

Contamination of the Earth's biosphere by toxic cometary hydrocarbons, in particular HCN, was suggested as a possible cause of extinctions associated with impacts (Hsü 1980).

However, the bulk of the cometary material will be vaporized in the impact fireball and few cometary molecules would survive the impact. The vaporized material would, of course, provide a rich volatile reservoir that would form new compounds as the fireball cools. However, the fraction of vaporized cometary material is still likely small as compared with the vaporized target rock and/or ocean, and thus likely a minor contributor to any subsequent atmospheric pollution.

The estimated diameter of a crater formed by an impactor is given by Melosh (1989) from Schmidt-Holsapple scaling as

$$D = 1.8 \; \rho_i^{0.11} \; \rho_t^{-0.33} \; g^{-0.22} \; L^{0.13} \; W^{0.22} \; \text{meters} \qquad (5)$$

where ρ_i and ρ_t are the densities of the impactor and the target, respectively, g is the acceleration of gravity, L is the diameter of the impactor, and W is the impact energy. If one takes $W = 0.5 \; m_i \; v_i^2 = 0.667 \; \pi \; \rho_i \; (L/2)^3 v_i^2$, where m_i and vi are the mass and velocity of the impactor, respective y, then

$$D = 1.34 \; \rho_i^{0.33} \; \rho_t^{-0.33} \; g^{-0.22} \; L^{0.79} \; v_i^{0.44} \; \text{meters} \qquad (6)$$

For impacts of equal energy, W, the lower density of the comet will result in a smaller equivalent crater than for a rocky or iron asteroid, even though the comet may be somewhat larger in diameter. Note however that the dependence on impactor density goes only as the cube root of density, so the effect will not be large. Cometary impactors might also be expected to create shallower craters because the low material strength of the comets will lead them to deposit most of their kinetic energy relatively close to the target surface.

Discussion

Active long- and short-period comets provide between 20% and 30% of the potential

major impactors on the Earth (Shoemaker et al, 1990; Weissman 1990a). The uncertainty in the cratering estimates reflect the current poor state of knowledge of the cometary mass distribution, as well as the lack of detailed knowledge of the flux of both long- and short-period comets, Additional uncertainty comes from the possible existence of large numbers of extinct cometary nuclei. Comets may represent a particularly difficult threat to deal with because of the short warning times which might occur for long-period comets on an impacting trajectory.

Further research into the nature of cometary nuclei is required to provide the knowledge necessary for understanding their potential threat and for developing technologies for deflection or destruction of hazardous nuclei. These should include ground-based studies such as the proposed Spaceguard Survey (Morrison 1992), as well as follow-up physical studies using Earth-based and Earth-orbiting telescopes. However, the small size of the cometary nuclei demands that they can only be adequately explored with spacecraft missions which can observe the nuclei at close range and directly sample cometary materials. In particular, rendezvous missions are required which can collect materials at low velocities such that they are not vaporized or otherwise altered, and which can observe the nucleus as it transitions from its dormant state at large heliocentric distances, through its active phases around perihelion, and back to dormancy as activity declines. By necessity, spacecraft missions can only be planned to short-period comets whose returns can be accurately predicted. However, the possibility of a fast fly-through of a new long-period comet is an intriguing idea and one worthy of some additional study.

One mission that would have gone a great way towards providing the necessary information was the Comet Rendezvous Asteroid Fl yby mission (Weissman and Neugebauer 1992), which was canceled in 1992 for budgetary reasons. CRAF'S complement of remote sensing and *in situ* dust and gas sampling instruments would have provided a quantum leap

forward in our knowledge of cometary nuclei, as well as providing an accurate bulk density measurement and other relevant observations of a cometary nucleus. The demise of that mission was a tremendous loss for this area of research.

The European Space Agency is currently considering a comet rendezvous mission, called Rosetta (Schwehm and Langevin 199 1), which is very similar to CRAF and would provide much of the same information on the nucleus structure, morphology, density, and composition. That data is vital to further studies of the impact hazard problem. Thus, Rosetta should be given strong support by those interested in this problem.

Other missions under consideration include several, small Discovery class mission being looked at by NASA. Most of these missions involve flybys, often multiple flybys, of cometary targets. As such, these missions can only provide a modest amount of information on individual nuclei and will lack the detailed measurements possible with Rosetta. In particular, nucleus density will be very difficult to determine with flyby missions because of the low density of the comets, the high speed of the flybys, the poor determination of the nucleus volume (half hidden in shadow during the flyby), and the need to stay some modest distance from the nuclei for spacecraft safety as well as remote sensing needs. In addition, the limited payloads of the Discovery class missions are likely to leave many important questions unanswered. Multiple flyby missions can have some value in addressing the question of cometary diversity.

One Discovery class mission with higher potential is a planned low-cost rendezvous mission called Cometary Coma Chemical Composition, Because this mission plans a rendezvous it can determine the nucleus mass and density to high accuracy, can collect materials over a wide range of heliocentric distances, and can observe the rise and fall of cometary activity. In addition to dust and gas sampling mass spectrometers, the mission would include a simple

imaging system to be used for both science and spacecraft navigation,

References:

Aggarwal, H. R., and V. R. Oberbeck 1974. Roche limit of a solid body. Astrophys. J. 191:577-588.

A'Hearn, M. F. 1988. Observations of cometary nuclei. Ann. Rev. Earth Planet. Sci. 16:272-293.

A'Hearn, M. F., S. Hoban, P. V. Birch, C. Bowers, and D. A. Klinglesmith 1111986. Cyanogen jets in comet Halley. Nature 324:649-651.

A'Hearn, M, F,, and M. C. Festou 1990. The neutral coma. In *Physics and Chemistry of Comets, ed.* W, F. Huebner (Springer Verlag: Berlin), pp. 66-112.

Allen, M., M. Delitsky, W. Huntress, Y. Yung, W.-H, Ip, R. Schwenn, H. Rosenbauer, E. Shelley, H. Balsiger, and J. Geiss 1987. Evidence for methane and ammonia in the coma of comet Halley. Astron. Astrophys. 187:505-512.

Anders, E,, and E. Grevesse 1989. Abundances of the elements: Meteoritic and solar, Geochim. Cosmochim. Acts 53:197-214.

Bailey, M. A., and C. R. Stagg 1988. Cratering constraints on the inner Oort cloud and implications for cometary origins. Mon. Not. Roy, Astron. Sot. 23S: 1-32,

Beletic, J. W., R. M. Goody, and D. J. Tholen 1989. Orbital elements of Charon from speckle inter ferometry. *Icarus 79:38-46.*

Belton, M. J. S. 1991, Characterization of the rotation of cometary nuclei. In *Comets in the Post-Halley Era, eds.* R, L. Newburn, M. Neugebauer, and J. Rahe (Kluwer: Dordrecht), pp. 691-721.

Belton, M. J. S., W. H. Julian, A. J. Anderson, and B. E. A. Mueller 1992. The spin and homogeneity of comet Halley's nucleus. Icarus 93:183-193.

Bockelée-Morvan, D., Crovisier, J., Colom, D., Despois, D., and Paubert, G. 1990. Observations of parent molecules in comets P/Brorsen-Metcalf, Austin (1989c1) and Levy (1990c) at millimetre wavelengths: HCN, H_2S, H,CO, and CH_3OH. In *Formation of Stars and Planets,* ESA SP-3 15, pp. 143-148.

Bockelée-Morvan, D., P. Colom, J. Crovisier, D. Despois, and G. Paubert 1991. Microwave detection of hydrogen sulphide and methanol in comet Austin (1989c1). Nature 350:318-320.

Boice, D, C,, W. F. Huebner, M. J. Sablik, and 1. Konno 1990. Distributed coma sources and the CH_4 /CO ratio in comet Halley. Geophys. Res. Lett. 16:1813-1816.

Boss, A. P., A. G. W. Cameron and W. Benz 1991. Tidal disruption of inviscid planetesimals. Icarus 92:165-178.

Bowell, E., and B. G. Marsden 1992. 4015 (1979 VA) = Comet Wilson-Harrington (1949 111). IAU Circular 5585.

Brin, G. D., and D. A. Mendis 1979, Dust release and mantle development in comets. Astrophys. J.

229:402-408.

Brooke, T. Y., A. T. Tokunaga, H. A. Weaver, G. Chin, and T, R. Geballe 1991. A sensitive upper limit on the methane abundance in comet Levy (1990c). Astrophys. J.372:L1 13-116.

Burns J. A. and V. Safronov 1973. Asteroid nutation angles. Mon. Not. Roy. Astron. Sot. 165:403-411.

Bus, S. J., S. A. Stern, and M. F. A'Hearn 1991. Chiron: Evidence for historic cometary activity. In *Asteroids, Comets and Meteors 1991*, (Lunar & Planet Inst.: Houston), p, 34 (abstract).

Chyba, C. F., P. J. Thomas, and K. J. Zahnle 1993. The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid. Nature 361:41-44.

Colom, P., J. Crovisier, D. Bockelée-Morvan, D. Despois, and G, Paubert 1992. Formaldehyde in comets: 1. Microwave observations ofP/Brorsen-Metcalf(1989 X), Austin (1 989c 1), and Levy (1990c). Astron. Astrophys. 264:270-281.

Combes, M., Moroz, V. I., Crifo, J. F., Bibring, J. P., Coron, N., Crovisier, J., Encrenaz, T., Sanko, N., Grigoriev, A., Bockelée-Morvan, D., Gispert, R., Emerich, C., Lamarre, J. M,, Rocard, F., Krasnopolsky, V,, and Owen, T. 1986. Detection of parent molecules in comet Halley from the IKS-Vega experiment. In *Exploration of Halley's Comet, eds.* B. Battrick, E. J. Rolfe and R. Reinhard, ESA SP-250, 1:353-358.

Combes, M., Moroz, V. 1,, Crovisier, J., Encrenaz, T., Bibring, J. P., Grigoriev, A. V., Sanko, N. F., Coron, N., Crifo, J. F., Gispert, R., Bockelée-Morvan, D., Nikolsky, Yu. V., Krasnopolsky, V. A., Owen, T., Emerich, C., Lamarre, J. M., and Rocard, F, 1988. The 2.5-12 μm spectrum of comet Halley from the IKS-VEGA experiment, Icarus 76:404-436.

Crovisier, J., D. Despois, D. Bockelée-Morvan, P. Colom, and G. Paubert 1991. Microwave observations of hydrogen sulfide and searches for other sulphur compounds in comets Austin (1989c1) and Levy (1990c). Icarus 93:246-258.

Daniels, P. A. and D. W. Hughes 1981. The accretion of cosmic dust: a computer experiment. Mon. Not, Roy. Astron. Sot, 195:1001-1009.

Degewij, J., and E. F, Tedesco 1982. Do comets evolve into asteroids? Evidence from physical studies. In *Comets, ed.* L. L. Wilkening (University of Arizona Press: Tucson), pp. 665-695.

Delsemme, A. H., and D. A. Rud 1973. Albedos and cross-sections for the nuclei of comets 1969 IX, 1970 II, and 1971 II, Astron. Astrophys. 28:1-6.

Dobrovolskis, A. R. 1990. Tidal disruption of solid bodies. Icarus 88:24-38.

Dorm, B., P. A. Daniels, and D. W. Hughes 1985. On the structure of the cometary nucleus. Bull. Amer. Astron. Sot. 17:520 (abstract).

Dorm, B. 1991, The accumulation and structure of comets. In *Comets in the Post-Halley Era, eds.* R. L. Newburn, M. Neugebauer, and J. Rahe (Kluwer: Dordrecht), pp. 335-359.

Duncan, 1(4., T. Quinn, and S. Tremaine 1987. The formation and extent of the solar system comet cloud. Astron. J. 94:1330-1338.

Duncan, M., T. Quinn, and S. Tremaine 1988. The origin of short-period comets. Astrophys. J. 328: L69-L73.

Eberhardt, P,, D. Krankowsky, W. Schulte, U. Dolder, P. Lämmerzahl, J. J. Berthelier, J. Woweries, U. Stubbeman, R. R. Hodges, J. H. Hoffman, and J. M. Illiano 1987. The CO and N_2 abundance in comet P/Halley, Astron. Astrophys. 187:481-484.

Eberhardt, P., R. Meier, D. Krankowsky, and R. R. Hodges 1991. Methanol abundances in comet P/Halley from in-situ measurements. Bull. Amer. Astron. Sot. 23:1161 (abstract).

Everhart, E. 1967. Intrinsic distributions of cometary perihelia and magnitudes. Astron. J. 72:1002-1011.

Fanale, F. P., and J. R. Salvail 1984. An idealized short-period comet model: surface insolation, H_2O flux, dust flux, and mantle evolution. Icarus 60:476-511.

Feldman, P. D., Festou, M. C., A'Hearn, M. F., Arpigny, C., Butterworth, P, S., Cosmovici, C. B., Danks, A. C., Gilmozzi, R., Jackson, W. M., McFadden, L. A., Patriarch, P., Schleicher, D. G., Tozzi, G, P., Wallis, M. K., Weaver, H. A., and Woods, T. N. 1987. IUE Observations of comet P/Halley: Evolution of the ultraviolet spectrum between September 1985 and July 1986. Astron. Astrophys. 187:325-328.

Fernandez, J. A. 1988. End-states of short-period comets and their role in maintaining the zodiacal dust cloud. Moon & Planets 41:155-161.

Fernandez, J. A. and W .-H. Ip 1991. Statistical and evolutionary aspects of cometary orbits. In *Comets in the Post-Halley Era, eds.* R. L. Newburn, M. Neugebauer, and J, Rahe (Kluwer: Dordrecht), pp. 487-535.

Fink, U. 1992. Comet Yanaka (1988r): A new class of carbon-poor comet. Science 257:1926-1929.

Fraundorf, P., C. Hintz, O. Lowry, K. D. McKeegan, and S. A. Sandford 1982. Determination of the mass, surface density, and volume density of individual interplanetary dust particles, Lunar & Planet. Sci. Conf. 13:225-226 (abstract).

Geiss, J., Altwegg, K., Anders, E., Balsiger, H., Ip, W.-H., Meier, A., Neugebauer, M., Rosenbauer, H., and Shelley, E. G. 1991. Interpretation of the ion mass spectra in the mass per charge range 25-35 amu/e⁻ obtained in the inner coma of Halley's comet by the HIS-sensor of the Giotto IMS experiment. Astron. Astrophys. 247:226-234.

Gombosi, T. I. and H. L. F. Houpis 1986. An icy-glue model of cometary nuclei. Nature 324:43-46.

Greenberg, J. M., and J. 1. Hage 1990. From interstellar dust to comets: A unification of observational constraints, Astrophys. J. 361:260-274.

Hoban, S., M, Mumma, D. C. Reuter, M. DiSanti, R. R. Joyce, and A. Storrs 1991. A tentative identification of methanol as the progenitor of the 3.52 μm emission feature in several comets. Icarus

93:122-134.

Hsu, K. J. 1980. Terrestrial catastrophe caused by cometary impact at the end of the Cretaceus. Nature 285:201 -203,

Hughes, D. W. 1991. Possible mechanisms for cometary outbursts, In *Comets in the Post-Halley Era, eds.* R. L. Newburn, M. Neugebauer and J. Rahe (Kluwer: Dordrecht), pp. 825-851.

Ip, W.-H., Rosenbauer, H., Schwenn, R., Balsiger, H., Geiss, J., Meier, A., Goldstein, B. E., Lazarus, A. J., Shelley, E., and Kettmann, G. 1990. Giotto IMS measurements of the production rate of hydrogen cyanide in the coma of comet Halley. Ann. Geophys. 8:319-325.

Jessberger, E. K., A. Christoforidis, and J. Kissel 1988. Aspects of the major element composition of Halley's dust, Nature 332:691-695.

Jewitt, D., and J. Luu 1992. 1992 QB_1 . IAU Circular 5611.

Jewitt, D. C. and K. J. Meech 1988. Optical properties of cometary nuclei and a preliminary comparisons with asteroids. Astrophys. J. 328:974-986.

Johnson, R. E., J. F. Cooper, L.J. Lanzerotti, and G. Strazzula 1987. Radiation formation of a non-volatile comet crust. Astron. Astroph ys. 187:889-892.

Kaneda, E., K. Hirao, M. Takagi, O. Ashihara, T. Itoh, and M. Shimizu 1986. Strong breathing of the hydrogen coma of comet Halley, Nature 320:140-141.

Kawara, K., B. Gregory, T. Yamamoto, and H. Shibai 1988. Infrared spectroscopic observation of methane in comet P/Halley. Astron. Astrophys. 207:174-181.

Keller, H. U. 1987. The nucleus of comet Halley. In *Diversity and Similarity of Comets*, ESA SP-278, pp. 447-454.

Kim, S. J., M. F. A'Hearn, and S. M. Larson 1990. Multi-cycle fluorescence: Application to S_2 in comet IRAS-Araki-Alcock 1983d. Icarus 87:440-451.

Kleine, M,. S. Wyckoff, P, A, Wehinger, and B. A. Peterson 1991, The carbon isotope abundance ratios in comets. Bull. Amer. Astron. Sot. 23:1166 (abstract).

Krankowsky, D., Lämmerzahl, P,, Herrwerth, I., Woweries, J., Eberhardt, P,, Dolder, U., Herrmann, U., Schulte, W., Berthelier, J. J., Illiano, J. M., Hodges, R. R., and Hoffman, J. H. 1986. In situ gas and ion composition measurements at comet Halley. Nature 321:326-329.

Krasnopolsky, V. A,, and A. Yu. Tkachuk 1991, TKS-Vega experiment: NH and NH_2 bands in comet Halley, Astron. J. 101:1915-1919.

Kresak, L. 1985. The aging and lifetimes of comets. In *Dynamics of Comets: Their Origin and Evolution, eds.* A, Carusi and G. B. Valsecchi (D. Reidel: Dordrecht), pp. 279-302.

Kresak L. 1987. Dormant phases in the aging of periodic comets. Astron. Astrophys. 187:906-908.

Kuiper, G. P, 1951, On the origin of the solar system, In *Astrophysics, ed. J.* A. Hynek, McGraw Hill, New York, pp. 357-424.

Larson, H, P,, H. A. Weaver, M. J. Mumma, and S. Drapatz 1989. Airborne infrared spectroscopy of comet Wilson (19861) and comparisons with comet Halley. Astrophys. J. 338:1106-1114.

Lewis, J. S., G. H. Watkins, H. Hartman, and R. G. Prinn 1982. Chemical consequences of major impact events on Earth. In *Geological Implications of Impacts of Large Asteroids and Comets on the Earth, eds.* L. T. Silver and P. H. Schultz, Geol. Sot. Amer. Special Paper 190, pp. 215-221.

Luu, J., and D. Jewitt 1993. 1993 FW. IAU Circular 5730,

Magee-Sauer, K., F. Scherb, F. L, Roesler, J. Harlander, and B. L. Lutz 1989. Fabry-Perot observations of the NH_2 emission from comet Halley. Icarus 82:50-60.

Marconi, M. L., D. A. Mendis, A. Korth, R. P. Pin, D. L. Mitchell, and H. Reme 1990. The identification of H_3S^+ with the ion of mass per charge (m/q) 35 observed in the coma of comet Halley. Astrophys. J. 352: L17-L20.

Marsden, B. G. 1967. The Sun-grazing comet group. Astron. J. 72:1170-1183.

Marsden, B. G, 1989. The Sun-grazing comet group. II. Astron. J. 98:2306-2321.

Marsden, B. G., and G. V. Williams 1992. *Catalogue of Cometary Orbits, 7th* edition. Smithsonian Astrophysical Observatory, Cambridge, 100 pp.

McDonnell, J. A. M,, P. L. Lamy, and G. S. Pankiewicz 1991. Physical properties of cometary dust. In *Comets in the Post-Halley Era, eds.* R. L. Newburn, M. Neugebauer and J. Rahe (Dordrecht: Kluwer), pp. 1043-1073.

McSween, H. Y., and P. R. Weissman 1989. Cosmochemical implications of the physical processing of cometary nuclei. Geochim, et Cosmochim. Acts 53:3263-3271.

Meech, K. J., and Belton, M. J. S. 1989. 2060 Chiron. IAU Circular 4770.

Meech, K. J., and Belton, M. J. S. 1990. The atmosphere of 2060 Chiron. Astron. J. 100:1323-1338.

Meech, K. J., M. J. S. Belton, B. E. A. Mueller, M. W. Dicksion, and H. R. Li 1993, Nucleus properties of P/Schwassmann-Wachmann 1. *Asteroids, Comets, and Meteors 1993,* 212 (abstract).

Melosh, J. 1989. *Impact Cratering: A Geologic Process.* Oxford Univ. Press, New York. 284 pp.

Minis R. L. and D. G. Schleicher 1986. Rotational period of Comet Halley. Nature 324:646-649.

Minis, R. L., M. F. A'Hearn, and H. Campins 1988. An investigation of the nucleus and coma of P/Arend-Rigaux. Astrophys. J. 324:1194-1209.

Morrison, D. (cd.) 1992. *The Spaceguard Survey: Report of the NASA International Near-Earth Object Detection Workshop,* NASA, 68 pp.

Mumma, M, J., H. A. Weaver, H. P. Larson, D. S. Davis, and M. Williams 1986. Detection of water vapor in Halley's comet. Science *232:1523-1528.*

Mumma, M. J., and D. C. Reuter 1989. On the identification of formaldehyde in Halley's comet, Astrophys. J. 344:940-948.

Mumma, M. J., D. Reuter, and K. Magee-Sauer 1990. Heterogeneity of the nucleus of comet Halley. Bull. Amer. Astron. Sot. 22:1088 (abstract),

Mumma, M. J., S. A. Stern, and P. R. Weissman 1993a. Comets and the origin of the solar system. In *Planets and Protostars III, eds,* E. H. Levy and J, L. Lunine (University of Arizona Press), pp. 1177-1252.

Mumma, M. J., S. Hoban, D. C. Reuter, and M, DiSanti 1993b. Methanol in recent comets: Evidence for two distinct cometary populations, *Asteroids, Comets, Meteors 1993,* 227 (abstract).

Oort, J. H. 1950. The structure of the cloud of comets surrounding the solar system and a hypothesis concerning its origin, Bull. Astron. Inst. Netherlands 11:91-110.

Öpik, E. J. 1963. The stray bedim in the solar system. Part I. Survival of cometary nuclei and the asteroids. Adv. Astron. Astrophys. 2:219-262.

Peale, S. J. 1989. On the density of Halley's comet. Icarus 82:36-49.

Peale, S. J. and J. J, Lissauer 1989. Rotation of Halley's comet. Icarus 79:396-430.

Prialnik, D., and A. Bar-Nun 1988. The formation of a permanent dust mantle and its effect on cometary activity. Icarus 74:272-283.

Rickman, H. 1986. Masses and densities of comets Halley and Kopff. In *The Comet Nucleus Sample Return Mission,* ESA SP-249, pp. 195-205.

Rickman, H, 1989. The nucleus of comet Halley: Surface, structure, mean density, gas and dust production. Adv. Space Res. 9, No. 3, 59-71.

Rickman, H, 1991. The thermal history and structure of cometary nuclei. In *Comets in the Post-Halley Era, eds* R. L. Newburn, M. Neugebauer and J. Rahe (Kluwer: Dordrecht), pp. 733-759.

Sagdeev, R. Z., G. A. Avanesov, V. A. Shamis, K. Szegö, E. Merenyi, B. A. Smith, Ya. L, Ziman, V, A, Krasikov, V. A. Tarnopolsky, and A, A, Kuzim 1986a. TV experiment in Vega mission: Image processing technique and some results, In *Exploration of Halley 's Comet, eds.* B. Battrick, E. J. Rolfe, and R. Reinhard, ESA SP-250, 2:295-305.

Sagdeev, R. Z., V. A. Krasikov, K. Szegö, I. Toth, B. Smith, S. Larson, E. Merenyi, V. A. Shamis, and V. L. Tarnopolsky 1986b. Rotation and spin axis of comet Halley. In *Exploration of Halley's Comet, eds.* B. Battrick, E. J. Rolfe, and R. Reinhard, ESA SP-250, Vol. 2, pp. 335-338.

Sagdeev, R. Z., P. E., Elyasberg, and V. I. Moroz 1988. Is the nucleus of comet Halley a low density body? Nature 308:240-242.

Samarasinha, N. H. and M. F. A'Hearn 1991. Observational and dynamical constraints on the rotation of comet P/Halley, Icarus 93:194-225.

Schleicher, D. G., S. J. Bus, and D. J. Osip 1993. The anomalous molecular abundances of comet P/Wolf-Barrington. Icarus, in press.

Schwehm, G. H., and Y. Langevin 1991. *Rosetta: A Comet Nucleus Sample Return Mission,* ESA SP-1125, 189 pp.

Sekanina Z, 1981, Rotation and precession of cometary nuclei, Ann. Rev. Earth Planet, Sci. 9:113-145.

Sekanina, Z, 1982. The problem of split comets in review. In *Comets,* ed. L. L. Wilkening (University of Arizona Press: Tucson), pp. 251-287.

Sekanina Z. 1988. Outgassing asymmetry of periodic comet Encke II. Astron. J. 96:1455-1475.

Sekanina, Z., and S. M. Larson 1984, Coma morphology and dust-emission pattern of periodic comet Halley. 11. Nucleus spin vector and modeling of major dust features in 1910. Astron. J. 89:1408-1425.

Sekanina, Z., and D. K. Yeomans 1985. Orbital motion, nucleus precession and splitting of periodic comet Brooks 2. Astron. J. 90:2335-2352.

Shoemaker, E. M., R. F. Wolfe, and C. S. Shoemaker 1990. Asteroid and comet flux in the neighborhood of Earth. In *Global Catastrophes in Earth History, eds.* V, L. Sharpton and P. D. Ward, Geol. Sot. of Amer. Special Paper 247, pp. 155-170.

Shoemaker, E. M., D. Levy, and C. S. Shoemaker 1993. Comet Shoemaker-Levy 1993e. IAU Circular 5725,

Smoluchowski, R. 1981. Amorphous ice and the behavior of cometary nuclei. Astrophys. J. 244: L31-L34.

Sridhar, S. and S. Tremaine 1992. Tidal disruption of viscous bodies. Icarus 95:89-99.

Stern, S.A. 1986. The effects of mechanical interaction between the interstellar medium and comets, Icarus 68:276-283.

Stern, S. A. 1990. ISM induced erosion and gas dynamical drag in the Oort cloud. Icarus 84:447-466.

Stern, S, A,, and J. M. Shun 1988. 'he thermal evolution of comets in the Oort cloud by passing stars and stochastic supernovae. Nature 332:407-411.

Stewart, A. 1. F. 1987. Pioneer Venus measurements of H, O, and C production in comet Halley near perihelion. Astron. Astrophys. 187:369-374.

Sykes, M. V,, and R. G. Walker 1991. Constraints on the diameter and albedo of 2060 Chiron. Science 251:777-780.

Sykes, M, V., and R. G. Walker 1992. Cometary dust trails, 1: Survey. Icarus 95:180-210.

Szegö, K." 1991. P/Halley, the model comet inviewof theimagining experiment aboard the VEGA experiment. In *Comets in the Post-Halley Era*, eds. R. L. Newburn, M. Neugebauer, and J. Rahe (Kluwer: Dordrecht), pp. 713-732.

Tyler, G. L., D. N. Sweetnam, J. D. Anderson, S. E. Borutzki, J. K. Campbell, V. R. Eshelman, D. L. Gresh, E. M. Gurrola, D. P. Hinson, N. Kawashima, E. R. Kursinski, G. S. Levy, G. F. Lindal, J. R. Lyons, E. A. Marouf, P. A. Rosen, R. A. Simpson, G. E, Wood 1989. Voyager radio science observations of Neptune and Triton. Science 246:1466-1473.

Vanysek, V. 1991, Isotopes in Comets. In *Comets in the Post-Halley Era, eds.* R. L, Newburn, M. Neugebauer, and J, Rahe (Kluwer: Dordrecht), pp. 879-896,

Weissman, P. R. 1980. Physical loss of long-period comets. Astron. Astrophys. 85:191-196.

Weissman, P. R. 1982. Terrestrial impact rates for long and short-period comets. In *Geological Implications of Impacts of Large Asteroids and Comets on the Earth,* eds. L. T. Silver and P, H. Schultz, Geol. Sot. Amer. Special Paper 190, pp. 15-24.

Weissman, P. R. 1986, Are cometary nuclei primordial rubble piles? Nature 320, 242-244.

Weissman, P. R. 1990a. The cometary impactor flux at the Earth, In *Global Catastrophes in Earth History,* eds V. Sharpton and P. Ward, Geol. Sot. America Special Paper 247, Boulder, pp. 171-180.

Weissman, P. R. 1990b. Physical processing of cometary nuclei since their formation. In *Comet Halley: Investigations, Results, Interpretations,* ed. J, Mason (Ellis Horwood: Chichester), 2, 241-257.

Weissman, P, R, 1991. Dynamical history of the Oort cloud. In *Comets in the Post-Halley Era, eds.* R, L, Newburn, M, Neugebauer, and J. Rahe (Kluwer: Dordrecht), pp. 436-486.

Weissman, P. R., and H. H. Kieffer 1981. Thermal modeling of cometary nuclei. Icarus 47:302-311.

Weissman, P, R., M. F. A'Hearn, L. A. McFadden, and H. Rickman 1989. Evolution of comets into asteroids, In *Asteroids II,* eds. R. P. Binzel, T. Gehrels, and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 880-920.

Weissman, P. R., and M. Neugebauer 1992. The comet rendezvous asteroid flyby mission: A status report. In *Asteroids, Comets, Meteors 1991, eds.* A. W. Harris and E. Bowell (Lunar and Planet, Inst.: Houston), pp. 629-632.

Weissman, P. R., and H. Campins 1993. Short-period comets. In *Resources of Near-Earth Space, eds.* J. S. Lewis and M. S. Matthews (University of Arizona Press, Tucson), in press,

Wetherill, G. W. 1971. Cometary versus asteroidal origin of chondritic meteorites. In *Physical Studies of Minor Planets,* ed. T. Gehrels, NASA SP-267, pp. 447460.

Wetherill, G. W. 1975. Late heavy bombardment of the moon and terrestrial planets. In *Proc. 6th Lunar Sci. Conf.,* pp. 1539-1561.

Wetherill, G. W, 1988. Where do the Apollo objects come from? Icarus 76:1-18,

Wetherill, G. W. 1991. End products of cometary evolution; Cometary origin of Earth-crossing bodies of asteroidal appearance. In *Comets in the Post-Halley Era, eds.* R. L. Newburn, J. Rahe, and M. Neugebauer (Dordrecht: Kluwer), pp. 537-556.

Whipple, F. L. 1950. A comet model I. The acceleration of Comet Encke. Astrophys. J. **112:375-394.**

Whipple, F. L. 1951. A comet model II. Physical relations for comets and meteors. Astrophys. J. **113:464-474.**

Whipple, F, L. 1982. The rotation of comet nuclei. In *Comets*, ed. L, L. Wilkening (University of Arizona Press: Tucson), pp. 227-250.

Woods, T. N., P. D. Feldman, K. F. Dymond, and D. J. Sahnow 1986. Rocket ultraviolet spectroscopy of comet Halley and abundance of carbon monoxide and carbon. Nature **324:436-438.**

Wyckoff, S., S. C. Tegler, and L. Engel 1991. Ammonia abundances in four comets. Astrophys. J. **368:279-286.**

Table 1.   Observed Cometary Nuclei .

Comet	R_{eff}[a] (km)	Axial Ratio	P_V	Color	P_{rot} (hr)	Q(r) (seC-')	r (AU)
Halley	5.5[b]	2.0	0.04	neutral, red	53 ?, 89 ?, 177 ?	6×10^{29}	0.8
Arend-Rigaux	5.2	>1.6	0.03	neutral, red	13.5	2×10^{26}	1.58
Neujmin 1	10.4	>1.65	0.02	very red	12.7	2×10^{26}	1.68
Schwassmann-Wachmann 1	15.4, 8.6 ?'	small ?	0.13 ?	red in near IR	14.0, 32.3 ?[c]		
Tempel 2	5.6	1.9	0.02	very red	8.9	2×10^{27}	1.71
Encke	< 2.2, 1.?	>2.0 ?			22.4 ?	6×10^{28}	0.76
IRAS-Araki-Alcock	4.0 ?				48-72?	2×10^{28}	1.03
Chiron	< 186.		>0.27	neutral	5.92		

" From Weissman and Campins (1993). References to original data sources are given in that paper.

Notes to Table 1.

a. $R_{eff} = \sqrt{ab}$ where a and b are the projected semi-axes at maximum light.
b. Actual Halley nucleus dimensions: 15 x 8 x 7 km.
c. New values from Meech et al. (1993).

Table 2.   Spectral Identifications in Comets

	Spectral range
Coma	
CN, ^{13}CN, C_2, $^{12}C^{13}C$, C_3, CH, NH, NH_2, OH, [01], Na, Ca, Cu, Cr, Mn, Fe, Ni, K, Co, SH CO+, CH^+, CO_2^+, N_2^+, OH+, Ca^+, H_2O^+	visible
H, C, O, S, OH, CO, CS, CO_2^+, CO+, CN^+, c+, S_2	ultraviolet
H_2O, H_2CO, CO_2, CO, CH_3OH, (OCS)[a] "C-H" feature near 3.4 μm of complex organic compounds, "silicate" emission feature near 10 μm	infrared
OH, HCN, H_2CO, H_2CS, H_2S, OCS (CH_3CN, NH_3, H_2O)[b]	radio
Ions of H, N, O, C, S_2, H_3O, NH_4, NH_3, NH_2, CH_5, CH_4, CH_3, C_3H_3, C_3H_4, C_3H, CS_2, CS, H_3S, $(H_2CO)_n$, H_2O, CO, N_2, C_2H_4, Many molecules, probably hydrocarbons, with mass up to 105 amu. **"CHON"** grains (dust grains with hydrocarbon mantles or composed entirely of light elements, i.e., H, C, N, O molecules).	"in situ" measurements by mass spectrometers during spacecraft flybys of comet Halley
Plasma tail	
Ions of CO, CH, CO_2, N_2, OH, H_2O, CN, OH, NH_4, SH	visible and ultraviolet

[a] Tentative identification

[b] Identification claimed in the past, but not confirmed in comet Halley

Table 3.   Abundance of Probable Parent Molecules in the Coma of Comet Halley"

Molecule	Relative Abundance	Comments
Comet Halley		
H_2O	100	Remote and *in situ* detections [1]
c o	~ 7	Direct (native) source [2]
	~ 8	Distributed source [2]
H_2CO	0-5	Variable [3]
co*	3	Infrared (Vega 1 IKS)
CH_4	< 0.2 -1.2	Ground-based infrared [4]
	0-2	Giotto IMS [5]
NH_3	0.1 -0.3	Variable, [6] Based on NH_2
	1 - 2	Giotto NMS [7]
HCN	0.1	Variable, Ground-based radio
	< 0.02	Giotto IMS
N_2	~ 0.02	Ground-based N_2^+ emission
SO_2	< 0.002	Ultraviolet (IUE)
H_2S	....	Giotto IMS [8]
CH_3OH	~ 1	Giotto NMS and IMS [9]
Other Comets		
c o	20	West (1976 VI)
	2	Bradfield (1979X)
	1 - 3	Austin (1989c1)
CH_4	< 0.2	Levy (1990c) 10
	1.5 -4.5	Wilson (1987 VII) [11]
CH_3OH	1 - 5	Variable [12]
H_2CO	0.1-0.04	If a parent species [13]
HCN	0.03 -0.2	Several comets [14]
H_2S	0.2	Austin (1989c1); Levy (1990c) [15]
S_2	0.025	IRAS-Araki-Alcock (1983 VII) [16]

" from Mumma et al. (1993a)

Notes to Table 3.

1) Water was detected directly by infrared spectroscopy (Mum ma et al, 1986; Combes et al. 1986) and by mass spectroscopy (Krankowsky et al. 1986).

2) CO was detected directly at ultraviolet wavelengths (Feldman et al. 1987; Woods et al. 1986, 1987) and in neutral mass spectra (Eberhardt et al. 1987). A tentative detection at infrared wavelengths (Combes et al. 1988) provided production rates in agreement with the native source.

3) The H_2CO abundance is variable, relative to water. The largest value found for comet Halley was 4.5 % $\pm$ 0.5%, measured by both **IKS** and Giotto NMS (also **IMS),** but at other times the production rates were 10 times smaller **(Mumma** and Reuter 1989). The values retrieved for comets Austin and Levy were much smaller than the values found in comet Halley.

4) Retrieved from a single spectral line of CH_4. The range reflects the uncertainty in rotational temperature for cometary CH_4 (50-200 K). The extrapolation from a single line to the ensemble production rate is therefore high] y uncertain. See **Kawara** et al. (1988).

5) The production rate retrieved from the neutral mass spectra on **Giotto** is highly model dependent, and could be zero in comet Halley (Allen et al. 1987; **Boice** et **al.** 1990). **Brooke** et **al.** (1991) recently found $CH_4 < 0,2\%$ in comet Levy **(1990c).**

6) Assuming that NH_2 is **produced** solely from NH_3 **(Magee-Sauer** et al. **1989;** Mumma et al. 1990; **Krasnopolsky** and Tkachuk 1991; Wyckoff et al. 1991).

7) Allen et al. (1987). **Boice** et al. (1990) **re-analyzed** the NMS spectra, retrieving 1%, while **Ip** et al. (1990) retrieved 0.5% from the **Giotto IMS** data.

8) Marconi et al. (1990). An incorrect lifetime was used in deriving the abundance of H_2S **(see Crovisier** et al. 1991).

9) See **Geiss** et al. (1991) and **Eberhardt** et al. (1991).

1 **0)** Based on ground-based infrared spectroscopy **(Brooke** et al. 1991). "'

11) Based on airborne infrared spectroscopy (Larson et al. 1989).

12) The value in comet Levy was $\sim$ 1%, but in **comet** Austin it was about 5% **(Bockelée-** Morvan et al. 1991; **Bockelée-Morvan,** personal communication; **Hoban** et al. 1991).

13) 0.1 % in comet Austin **(1989c1),** and 0.04% in **comet Levy (1990c). The** production rate would be about ten-fold larger **if** formaldehyde were a daughter **product (Colom** et al. **1992).**

14) In **P/Brorsen-Metcalf** (1989 X), Austin (1989c1), Levy **(1990c). Bockelée-Morvan** et al. 1990.

15) **Crovisier** et al. (1991).

16) Kim et al, (1990).

Table 4.   Average Atomic Abundances of Elements in Halley Dust Grains* .

Element	Halley		Solar System	C I - Chondrites
	Dust	Dust and Ice		
—¦	2,025	4,062	2,600,000	492
C	814	1,010	940	70.5
N	42	95	291	5.6
O	890	2,040	2,216	712
Na	10	10	5.34	5.34
Mg	= 100	= 100	= 100	= 100
Al	6.8	6.8	7.91	7.91
Si	185	185	93.1	93.1
S	72	72	46.9	47.9
K	0.2	0.2	0.35	0.35
Ca	6.3	6.3	5.69	5.69
Ti	0.4	0.4	0.223	0,223
Cr	0.9	0.9	1.26	1.26
Mn	0.5	0.5	0.89	0.89
Fe	52	52	83.8	83.8
Co	0.3	0.3	0.21	0.21
Ni	4.1	4.1	4.59	4,59

[1]   For comparison, the new solar system abundances and the CI-chondrite composition are also given (Anders and Grevesse 1989). The solar photospheric abundances of the listed elements are practically indistinguishable from the solar system abundances, with the exception of Fe, which has a photospheric abundance ratio of 123 (Anders and Grevesse 1989).

[2] From short spectra only.

" from Jessberger et al. (1988)

Table 5.   Stable Isotopes in Comets and Other Reservoirs

Species	Solar System	Local ISM'	Comets
D/H	2×10^{-5}	1.5×10^{-5}	$\geq 5 \times 10^{-4}$ [b]
D/H		1×10^{-4} to 1×10^{-2}'	
$^{12}C/^{13}C$	89	$43 * 4^{d}$	$100 * 15$ c'"
$^{12}C/^{13}C$		65 ± 20 [f]	70 to 130 [g]
$^{12}C/^{13}C$		12 to 110^{e}	10 to 1,000 [c,h]
$^{14}N/^{15}N$	270	≈ 400 [f]	> 200 ?
$^{16}O/^{18}O$	490	≈ 400 [f]	< 450 [c]
$^{24}Mg/^{25}Mg$	7.8		variable [c,h]
$^{25}Mg/^{26}Mg$	0.9		< 20
$^{32}S/^{34}S$	22.6		22 "[h]
$^{56}Fe/^{54}Fe$	15,8		15 [c,h]

See Vanysek (1991) for discussion and references for above data.

' ISM = interstellar matter
[b] Data for P/Halley only
[c] Range of observed values in dense ISM
[d] From visual spectra
[e] From ground-based observation of CN bands
[f] From radio astronomical data
[g] From ground-based observation of C_2 spectra
[h] From *in situ* mass spectrometry of dust

Figure Captions

Figure 1. Composite image of the nucleus of comet Halley taken by the Giotto spacecraft on March 14, 1986. The nucleus is silhouetted against the bright dust coma. The view is from a phase angle of -113°. The Sun is at the left. Bright dust jets emanate from discrete active areas on the nucleus, while other parts of the surface appear to be inactive. The resolution in the image varies from 800 meters/line-pair at lower right to ∼ 80 meters/line-pair in the upper left.

Figure 2. Image of the Halley nucleus taken by the Vega 2 spacecraft on March 9, 1986, at a range of -8,000 km, at near-zero phase. The "peanut" shape of the nucleus and the bright southern jet are clearly visible.

Figure 3. Relative distribution of absolute magnitudes, H_{10} , for long-period comets after correction for observational selection effects, as found by Everhart (1967). The scale of the nucleus masses at the bottom of the figure was derived with equation 1 (Weissman 1990a).

Figure 4. Four suggested models for the structure of cometary nuclei: a) the icy conglomerate model (Whipple 1950; drawing from Weissman and Kieffer 1981); b) the fractal model (Dorm et al, 1985); c) the primordial rubble pile (Weissman 1986); and d) the icy-glue model (Gombosi and Houpis 1986).   All but d) were suggested prior to the Halley spacecraft encounters in 1986..

Figure 5. Suggested physical processes which may alter the surfaces or interior of cometary nuclei over their lifetimes, including during storage in the Oort cloud and during passage close to the Sun. From McSween and Weissman (1989).

Figure 6. Interplanetary dust particle (IDP) recovered by high flying U-2 aircraft, 'I'he suspected cometary dust particle is an assemblage of submicron silicate and hydrocarbon grains. Inter-grain spaces were likely formerly filled by cometary ices. A 1.0 micron scale (10^{-6} meters) is at lower right. IDP's are also referred to as Brownlee particles because of the pioneering work of D. Brownlee in collecting and studying them.
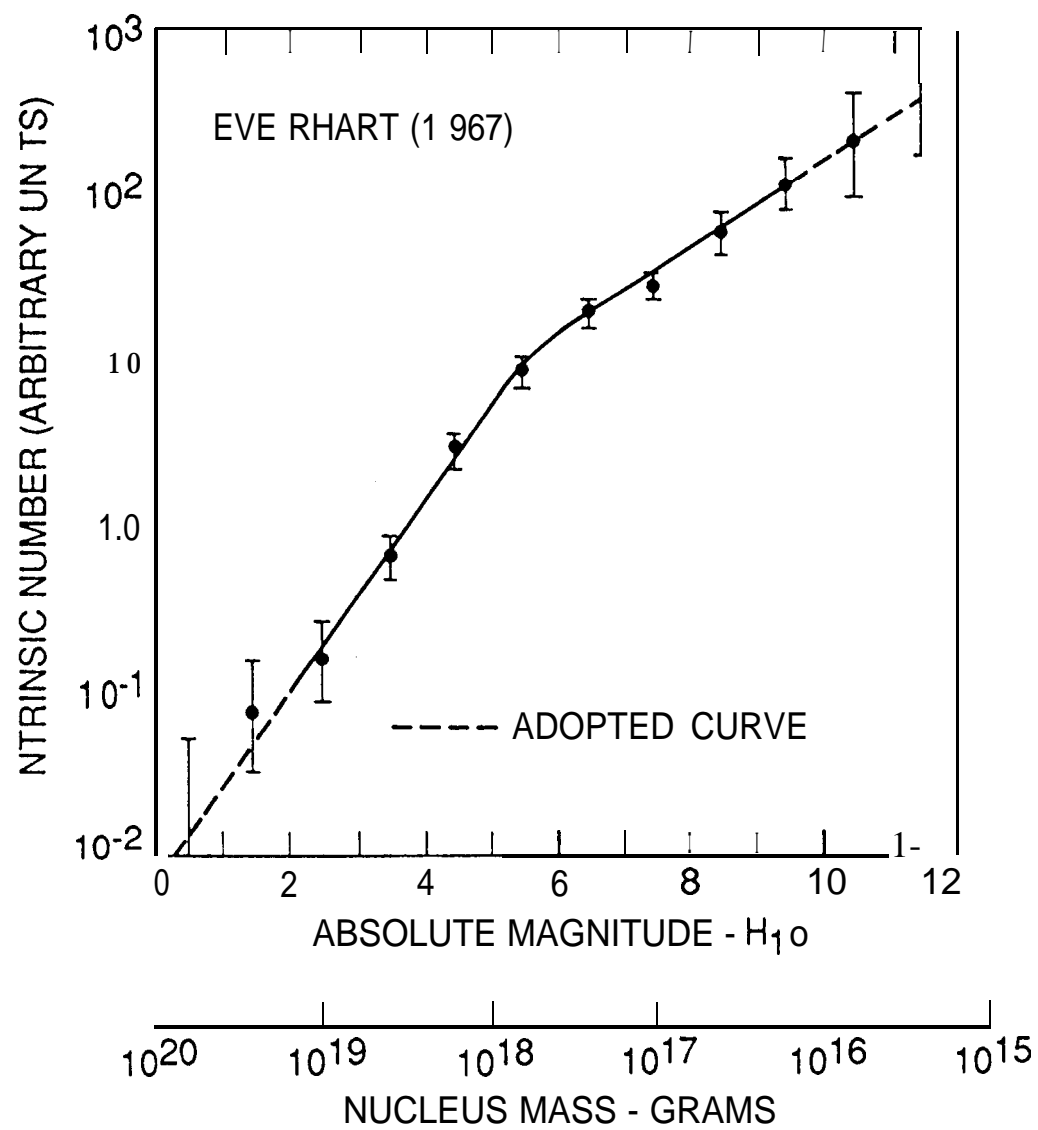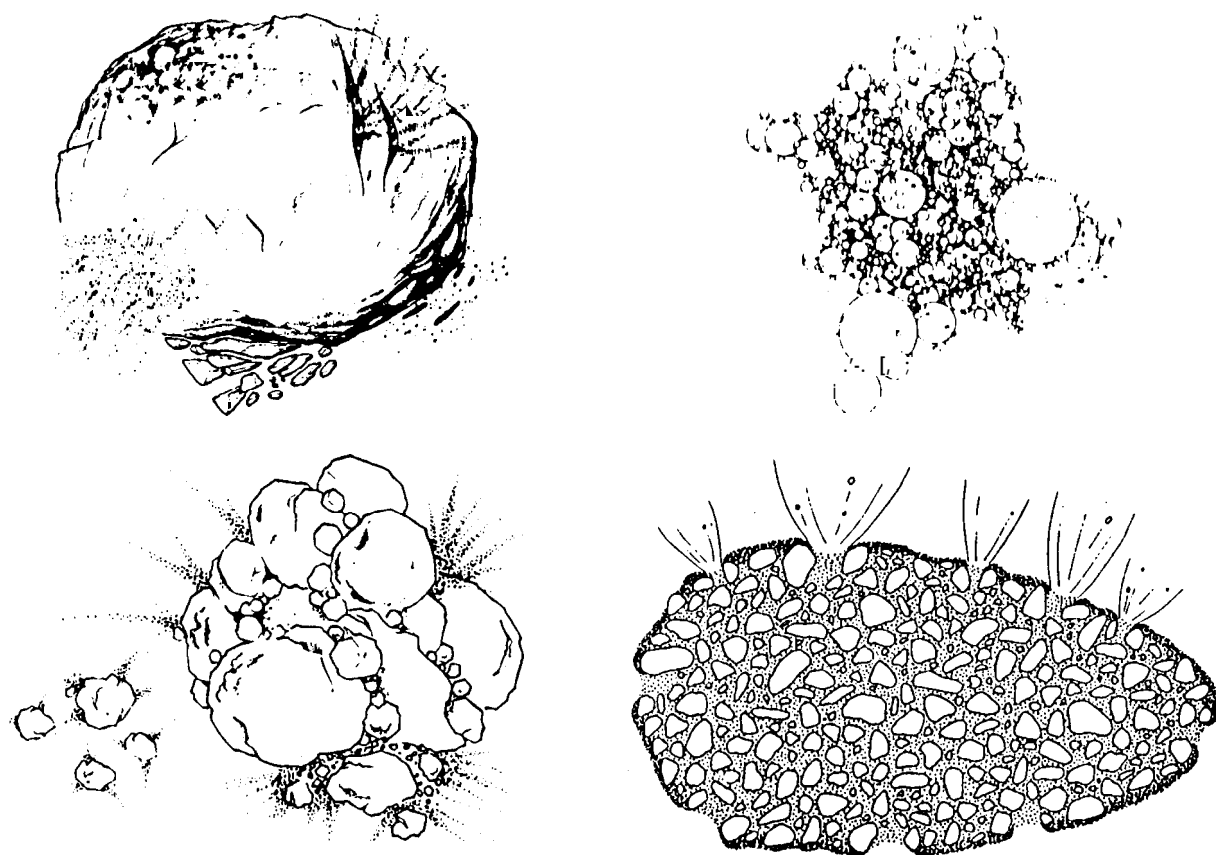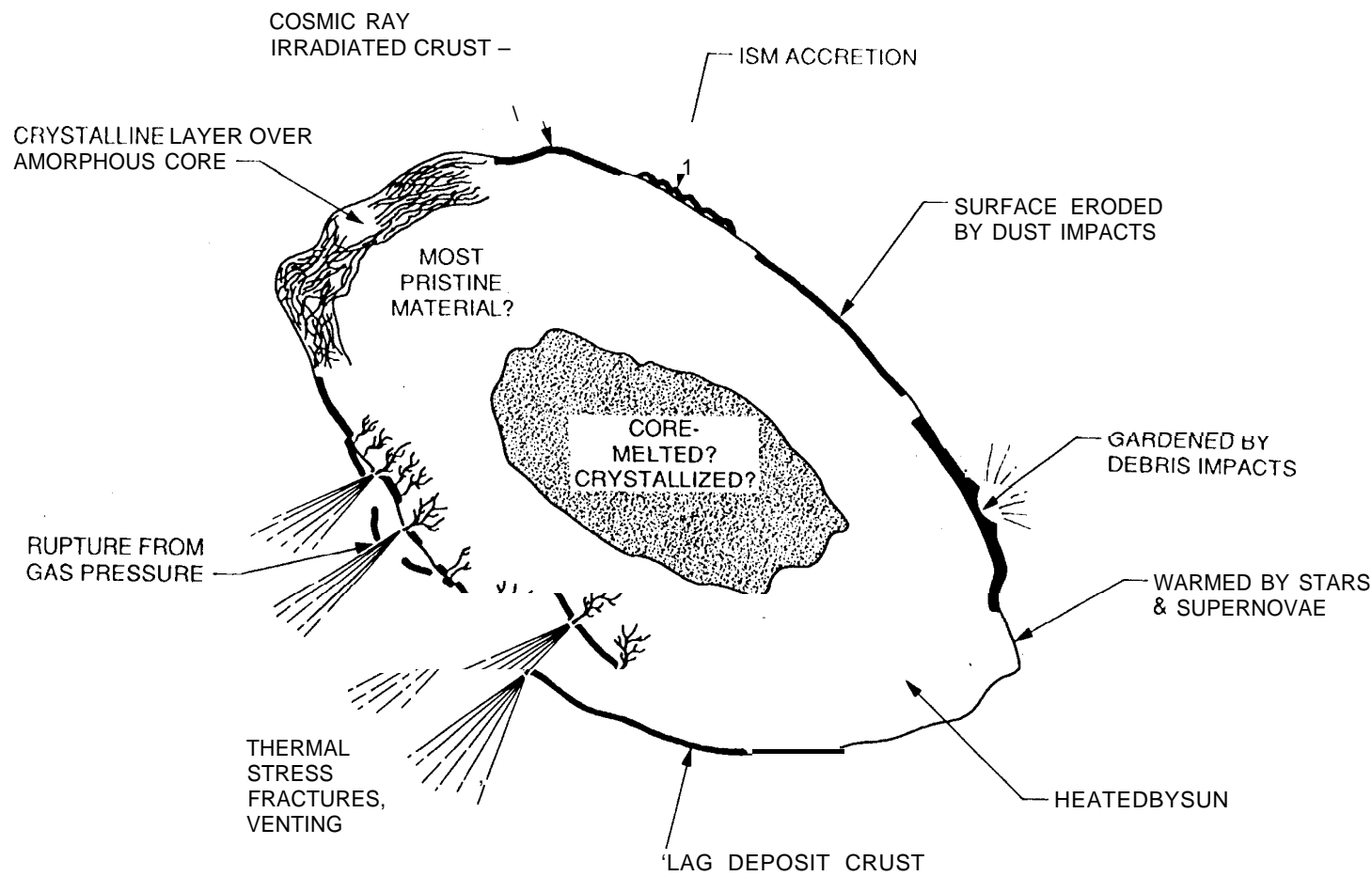
Figure 1.

Figure 2.

Figure 3.

47
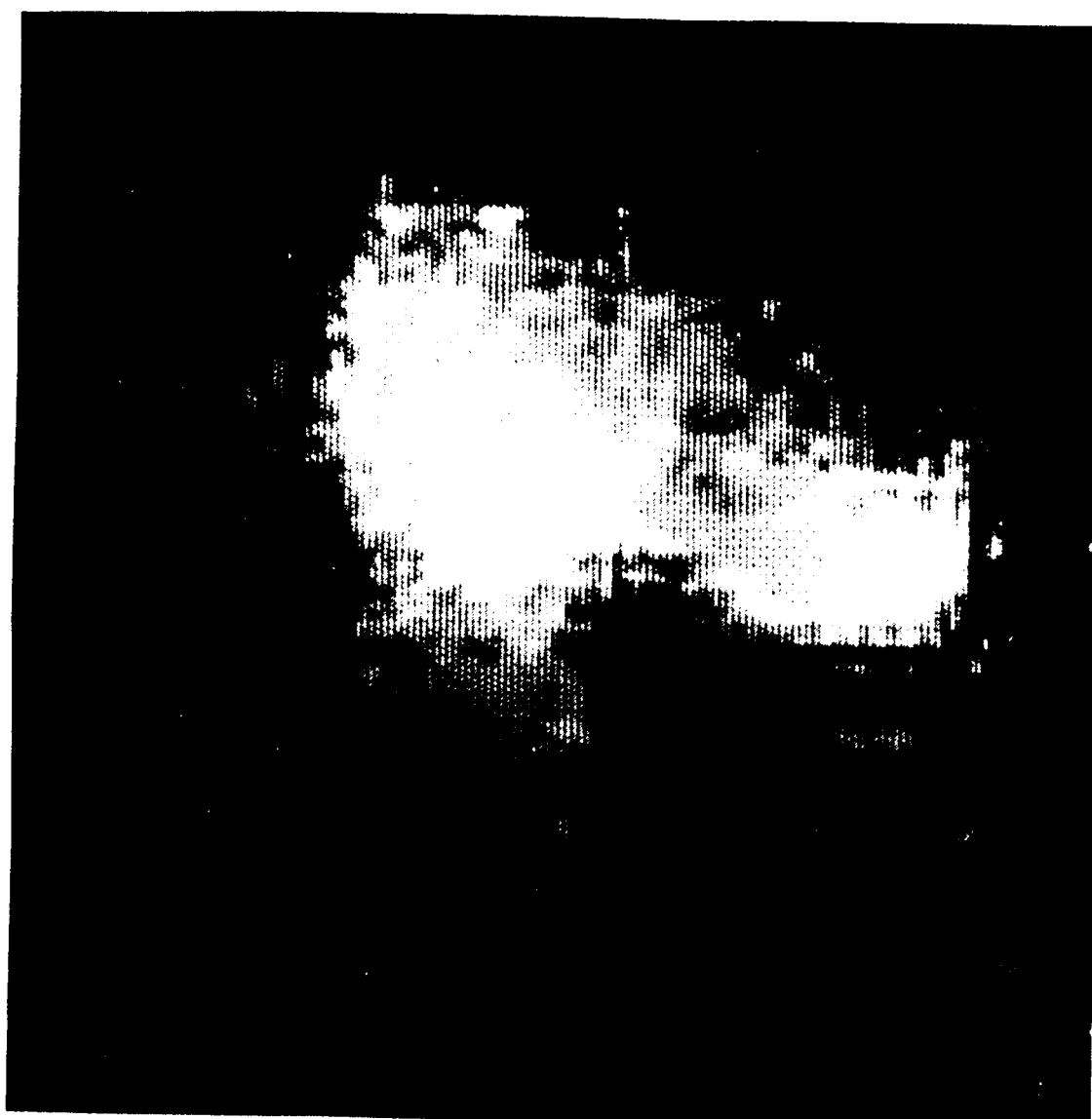
Figure 4.

Figure 5.

Figure 6.